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HEMISPHERE LATERALIZATION FOR COGNITIVE PROCESSING OF GEOMETRY*

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Abstract—A 54-item cross-modal visuo-tactile test involving geometrical discriminations in Euclidean, affine, projective and topological space (plane and 3-dimensional) was administered to 7 subjects with commissurotomy, 2 with hemispherectomy, 1 with agenesis of corpus callosum, and to 5 normal controls. Using blind manual stereognosis subjects selected one of a choice of three shapes, screened from sight, that best fitted a set of five different geometrical forms presented together on a panel in free vision. An intuitive apprehension of geometrical relations was involved that did not require formal training in geometry. Findings support a consistent minor hemisphere superiority and disclose orderly differences in left hemisphere capabilities correlated with the different types of geometry.

INTRODUCTION

IN PATIENTS with surgical disconnection of the hemispheres, arithmetical operations appear to be predominantly a left hemisphere function [1, 2]. Geometry, on the other hand, with its highly spatial structure would seem more likely to be processed in the right hemisphere, and anecdotal evidence supports this: one commissurotomy patient (L.B.) about 2½ yr after surgery was unable to do passing work in a public school class in geometry and had to be transferred to a class in "general mathematics". Another patient with congenital absence of corpus callosum (K.S.), a municipal college sophomore with an overall scholastic record near average, reported having exceptional difficulty with geometry [3–5]. In both cases, minor hemisphere lateralization was inferred on the basis, in the former in terms of inaccessibility to the language hemisphere, and in the latter on presumed developmental interference within the right hemisphere resulting from bilateralization of language including speech.

In the following we present the results of an effort to further investigate hemispheric lateralization for intuitive processing of geometrical relations. Subjects with commissurotomy, hemispherectomy and one with agenesis of the corpus callosum were administered a series of cross-modal visuo-tactile tests involving different levels and kinds of geometrical discriminations in Euclidean, affine, projective and topological space. The findings support a minor hemisphere superiority with orderly differences in left hemisphere capacities correlating with the four different types of geometry.

METHODS

Subjects

Five commissurotomy patients (N.G., N.W., R.Y., L.B., C.C.) with presumed midline section of inter-

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hemispheric commissures and with postoperative WAIS scores of 77, 93, 90, 106, 72, respectively [6], were all right-handed, ranged in age at the time of surgery from 13 to 43 yr and at the time of testing had post-operative recovery intervals of 8·5–11 yr. Additional brain damage of variable unknown extent is presumed to be present, but in none of these subjects is there an *a priori* reason this would be expected to bias significantly in favor of right hemisphere performance. Further details of the case histories are provided elsewhere [7, 8].

Two partial commissurotomy patients (N.F. and D.M.) with only the anterior two-thirds of the corpus callosum and the anterior commissure sectioned, were tested in their sixth and seventh year after surgery, at age 33 and 31. Their postoperative I.Q.'s measured with WAIS were 83 and 76 [9], both having higher verbal than performance scores. All commissurotomy subjects were patients of VOGEL and BOGEN.

Two hemispherectomy patients of VOGEL, one with nondominant hemispherectomy (D.W.), and one with dominant hemispherectomy (R.S.), were also tested. D.W., who was left-handed before surgery and in whom carotid amytal studies showed that speech was controlled by the left hemisphere, was a 7 yr old boy at the time of surgery and was 19 at the time of testing. R.S., a 16 yr old girl at the time of testing, was reported to be right-handed when dominant hemispherectomy was performed at age 10. They both had higher verbal than performance I.Q.'s measured with the WISC; the full score being 67 for D.W. and 56 for R.S. [10].

Another subject (V.K.) with X-ray diagnosis of total absence of corpus callosum [11] is right-handed, had graduated from a normal high school curriculum at age 18, and was 22 when tested.

The test was also administered to five right-handed normal adults with I.Q.'s in the normal range.

Testing procedure

Subjects sat at a table in front of an upright screen. An array of five geometrical forms on a background of black cardboard approximately 20 × 25 cm was presented for inspection in free vision. Behind the screen out of subject's view were placed three geometrical forms about 7 cm in longest dimension, only one of which conformed with the five-item visual display. The subject, after examining the five-sample array, was instructed verbally and by demonstration to reach beneath the screen with one hand and explore tactually the three unseen geometrical shapes, and to select, by use of a hand signal, the one that most resembles the forms in the array on the board (Fig. 1). Hemispheric lateralization was effected by restricting the stereognostic identification to one or the other hand. The three objects for tactual inspection were placed at 8 cm

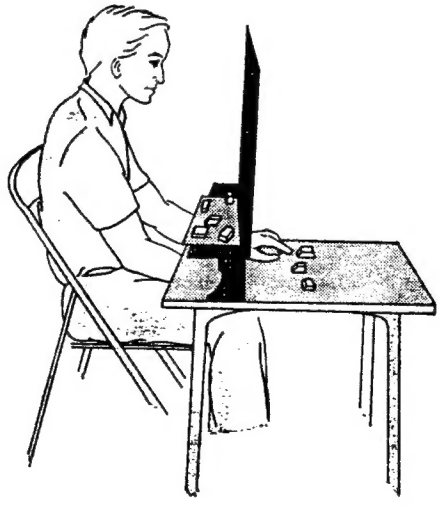

FIG. 1. The subject sitting at a table in front of an upright screen, is shown a five-item array and instructed to select by touch from among the three items presented out of sight, the one that belongs with the set presented visually.

distance from one another in a prearranged pseudorandom order, which was the same for both hands and for all subjects.

A total of 54 such sets of 8 geometric shapes for visuo-tactile matching was used, 22 involving problems in two-dimensional geometry, 32 in three-dimensional geometry. The two-dimensional shapes for visual inspection were made of paper cut-outs, the three-dimensional forms were cut from Styrofoam. All the

items for tactual examination were made in plastic or wood (Fig. 2). The two-dimensional and three-dimensional tests were administered separately, usually on different days. At each testing session the entire test of 22 choice-responses in one case and of 32 in the other was presented to the left hand first and after a 15 min break was repeated with the right hand. This schedule presumably gave an advantage to the right hand, and was adopted because it has been found that the left hemisphere tends to interfere with right hemisphere performance if the left is already familiar with the task [12], while the converse does not seem to be true.

The procedure was explained and demonstrated in simple preliminary trials until it was clear that the subjects were capable of performing a visual stereognostic matching of this kind, understood the task and were responding correctly with either hand. No reinforcement was given until the end of the session when the subject was told how he had performed. The subjects were asked not to talk and any sporadic questions and comments of the subject were ignored by the examiner during the left-hand performance in order not to distract the right hemisphere's concentration. During right-hand (left hemisphere) performance comments by the subject received quick, brief replies. When it was noticed that the first two patients worked more rapidly when using the left hand, the overall time required to complete the tests with each hand was recorded. Control tests involving direct matching-to-sample tasks were administered to determine the extent to which failures may have been due to stereognostic misinterpretation. From each of the 54 answer sets one form was chosen, usually the correct one, and was shown in free vision to the subject who was asked to retrieve by touch an identical form from among the choice of 3 behind the screen.

Experimental design: geometrical criteria

The tasks were designed to require an intuitive apprehension of geometrical relations without requiring any formal background on the part of the subject. In order to perform correctly, the subject was forced to make mental abstractions of the common characteristics of the set of five shapes in the visual array, and to match these with one of the shapes perceived tactually. The correct choice was in fact never identical to any of those presented for visual inspection but shared with them a variable number of geometrical characteristics.

In an effort to obtain a more refined screen for possible hemispheric differences the test was designed in four parts based on different kinds of geometry. Of the total 54 test tasks, 14 involved Euclidean, 14 affine, 14 projective and 12 topological principles. These vary characteristically in the number of defining spatial constraints to which each is subject, the greatest number being present in the Euclidean forms with progressively fewer in the affine, projective and topological sets, respectively. Thus the 5 items in each visual array plus the correct tactile choice belonged to a consistent geometrical set of forms definable in Euclidean, affine, projective or topological terms; while the two wrong choices did not belong to the same set.

RESULTS

Table 1 gives the overall percent correct scores obtained by each subject with right and left hands on the 2-D and 3-D parts of the test along with the time score for each hand and the percent correct for the combined totals. The obtained scores reflect an indisputable overall superiority of the right hemisphere and also show consistent and orderly differences within the left hemisphere with respect to the different kinds of geometries. The differences between left- and right-hand performance are further indicated in the histogram in Fig. 3. It is clear that the right hemisphere–left hand system consistently achieved better scores both in plane and in solid geometry. These differences range from 22 to 41% within commissurotomy subjects with a mean difference of 31% in plane geometry and 27% in solid geometry and a weighted difference of 28% for the whole test.

The left–right differences reflected in speed of performance were equally or more impressive than those indicated by error differences. The relative total time taken to perform the test with the left hand was generally less by a factor of 2 in the 7 commissurotomy subjects. The speed and also the degree of apparent confidence with which the subjects worked with the left hand reinforces further the evidence for superiority of the left hand–right hemisphere system.

The performance of the two hemispheres in the complete commissurotomy subjects is compared with respect to the different geometries in the histogram in Fig. 4. It may be seen

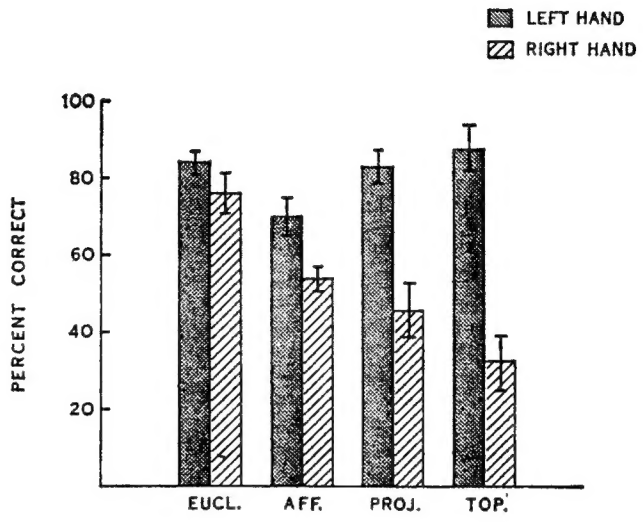

FIG. 4. Performance of complete commissurotomy subjects plotted for the different kinds of geometry.

This same laterality pattern was obtained also in the results with the two subjects with partial commissurotomy as well as in the subjects with left and right hemispherectomy. The speed and easy assurance with which the patient R.S. with left hemispherectomy went through the entire test was outstanding and most impressive, especially in comparison with the generally somewhat slower and sometimes hesitant performance of normals.

The patient with congenital absence of the corpus callosum obtained a lower percentage of correct answers with the left hand than the mean for complete commissurotomy with the same hand. His scores with the right hand were superior to those for all other patients.

The normal controls, who made a total of 9 mistakes in the 540 trials (54 items × 2 hands × 5 subjects) recorded, did not show any difference between the left and right hands in accuracy, assurance, or time. In the matching-to-sample control tests for stereognostic capability, as such, no mistakes were made by any of the subjects.

DISCUSSION

The overall superiority of the right hemisphere in these cross-modal tests for geometrical reasoning is apparent and consistent throughout. All the subjects with complete commissurotomy obtained high scores with the left hand in the 22 tasks involving two-dimensional discriminations, and also in the 32 discriminations of three-dimensional forms. Minor hemisphere performance in the case with dominant hemispherectomy was clearly superior to that in all of the complete commissurotomy subjects and to that of one of the partials. She equalled the score of two normal controls obtaining 94% correct answers as compared with the mean of 81% for the complete commissurotomy subjects and performed with a speed and a sense of assurance that equalled or surpassed even that of normal controls.

Conversely, the case with non-dominant hemispherectomy scored a low 48% correct, within one standard deviation from the mean of 53% for the left hemisphere in commissurotomy subjects, and significantly below the 62% mean score of the left hemisphere in

the subjects with partial commissurotomy. Although the partial commissurotomy subjects obtained slightly higher correct choice scores than those with complete commissurotomy, the same left–right disparity in performance was apparent also with respect to speed; that with the left hand being quicker and more direct and assured. It may be inferred accordingly that in the intact brain the interhemispheric functions involved in these tasks are not mainly mediated through the splenium but involve also more anterior commissural systems.

The present findings indicating right hemisphere dominance for geometrical reasoning are in line with other observations. Children are able to discriminate geometrical forms at a pre-school age while they are still incapable of verbalizing the defining features involved [13]. In adult processing as well as in chronological development geometrical properties and theorems can be intuitively understood well before a full verbal expression is possible. Introspectively the nonverbal visuo-spatial apprehension seems commonly to precede and support the sequential deductive analysis involved in the solution of geometrical problems.

The present evidence strongly suggests that such preverbal apprehension of geometrical relations is mainly a right hemisphere function. It seems therefore likely that right hemisphere operations are primary in the apprehension of geometrical properties of space and that these only subsequently become susceptible to verbalization. An active interaction of the two hemispheres during processing of geometrical problems seems implied and a similar interhemispheric integration would seem reasonable also for other cerebral activities involving spatial intuitions and their linguistic expression.

The marked differences within the left hemisphere as a function of the different kinds of geometry may be explained in part in terms of factors like the ease and difficulty of verbalization, the extent to which analytic processing is applicable, general familiarity, and the number of defining constraints involved. The left hemisphere performance scores seem to correlate in particular with the number of constraints or defining characteristics by which each of the four different types of gemoetrical tasks is governed. Where these restrictive geometrical properties are very numerous as in the Euclidean sets, the left hemisphere performed relatively well. Where the defining constraints become fewer as in the projective and especially the topological sets, the left hemisphere performance approaches chance level.

Increasing the number of spatial constraints that define the visual array of five forms necessarily increases the homogeneity and similarity of the items in the array and tends to focus the search for a tactual form that belongs. That this did not appear to affect scores of the right hemisphere in the same way may be ascribed in part to countering factors, in that hemisphere like an intrinsic ability of the right hemisphere to deal more effectively with topological than Euclidean space, or to the fact that the right hemisphere processing mechanisms are independent of the number of constraints. The presence of multiple constraints defining the Euclidean shapes may favor a sequential analysis by detail not possible for the topological forms which are scarcely analyzable into separate features. Richness of defining detail in the Euclidean tasks may also have facilitated verbal codification. A ceiling effect in the right hemisphere would seem excluded in that the scores did not go above 94% correct in the best subject (with a mean of 86%). Greater familiarity with Euclidean forms might also have played a role but alone would seem insufficient to account for the striking hemispheric differences in performance in the topological tasks.

The close correlation of left hemisphere performance with the number of defining geometrical constraints may suggest that what has been referred to as "ease of verbalization" of a task may correspond to varying degrees of mathematical limitations which can be

ordered in terms of class logic. Thus what are commonly referred to as "nonverbal" or "irregular" figures become "loosely structured" sets of shapes conveying very little information (as measured in information theory) and therefore not susceptible to decoding on the part of a hemisphere specialized in seeking for highly structured inputs (such as Euclidean figures and linguistic structures). On the other hand, the loosely structured shapes are entirely suited for right hemisphere processing which is not diverted by the search for details and therefore more readily captures holistic properties of sets independently of structural constraints. This would accord with the equal success with Euclidean and topological tasks in the right hemisphere.

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